Analytical Method for Water Vapor Collection and Analysis in Aircraft Cabin Fires

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16. Abstract

A method of collection and analysis was developed to determine the concentrations of water vapor in full-scale aircraft cabin fire tests as a function of time. Specialized collection tubes were developed which selectively trap water vapor. Particulates are filtered out of the sample stream and light fixed gases such as CO, CO_2, O_2, methane, propane, and butane pass through the tube. The gas collection sections of the tubes are surrounded by ice-water to maximize collection efficiency of the desiccant packing material. The percentage of water in the test atmosphere is calculated based on the weight gain of the tube and the volume of sample drawn. The flow is controlled by a calibrated needle valve, downstream of the sampling assembly, held at a constant temperature. The method was validated by analyzing selected components of a sample tube from a full-scale fire test by Thermogravimetric Analysis.

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EXECUTIVE SUMMARY

This report describes the method of collection and analysis developed to measure water vapor as a function of time for full-scale aircraft cabin fire tests.

Specialized collection tubes were developed which selectively trap water vapor. Particulates are filtered out of the sample stream and light fixed gases such as CO, CO_2, O_2, methane, propane, and butane pass through the tube. The gas collection sections of the tubes are surrounded by ice-water to maximize collection efficiency of the desiccant packing material. The tubes are weighed before and after a test. The percentage of water in the test atmosphere is calculated based on the weight gain of the tube and the volume of sample drawn. The flow is controlled by a calibrated needle valve, downstream of the sampling assembly, held at a constant temperature. The method was validated by analyzing selected components of a sample tube from a full-scale fire test by Thermogravimetric Analysis.

This procedure was used to evaluate the differences in water vapor released during a series of full-scale TC-10 cabin fire tests with and without aircraft cabin water spray fire suppression.

INTRODUCTION

PURPOSE.

The purpose of this work is to develop a method of quantifying water vapor in the presence of a complex mixture of airborne combustion products, to verify that this method is relatively free of interferences, and to demonstrate the applicability of this method to measure water vapor as a function-of-time in an aircraft cabin fire with and without water spray.

This data was used to access whether there is an additional thermal inhalation hazard from the water vapor generated by water mist suppression of aircraft cabin fires.

BACKGROUND.

Concentrations of water vapor were expected to be very high for a baseline aircraft cabin fire test. Water is a product of combustion for many materials. Using methane as an example, for every mole of CO_2 produced by the combustion of methane, 2 moles of water are produced. Concentrations of 10 percent of CO_2 are often seen for full scale fire tests. Corresponding concentrations of 20 percent water would be expected if methane were the fuel.

Cabin water spray systems may result in vaporization of high volumes of water. A gravimetric procedure for measuring these high water vapor levels was selected over more elaborate instrumental methods. It would avoid the need for heated filters and sample lines, would be self-calibrating and could be quickly assembled from readily available materials. The ice-water bath housing is the same used for past acid gas sampling in the TC-10 (reference 1).

DISCUSSION

COLLECTION.

Specialized collection tubes were developed to collect water samples in the TC10 fire tests. The tube is constructed of Teflon FEP, is transparent, and is 10 1/2 inches long with a 1/4-inch outside diameter (o.d.) and 4.8 millimeter (mm) inside diameter (i.d.). It is packed with 10 to 20 mesh indicating drierite, anhydrous calcium sulfate, for a 3 1/4-inch length on the downstream end of the tube, as indicated in figure 1. Teflon retainers and glass wool hold the drierite in place. Further upstream within the tube are seven 3 mm diameter solid glass beads which serve to cool down the hot gas stream. A glass wool filter is located within the upstream end of the tube to trap particulates. Teflon retainers hold the glass wool and beads in position.

The tubes are mounted horizontally through an ice-water bath perpendicular to the expected smoke velocity vector. This housing is illustrated in figure 2. The container is an aluminum box insulated with 1/2 inch KAOWOOL™ board insulation. There are 12 tubes mounted through the front face of the box. Ten are sample tubes and 2 serve as controls. The tubes are held in place with drilled through Swagelock bulkhead fittings, such that each tube slips through the fitting, and extends 3 1/4 inches outside the metal box. Water-tight vespel ferrules replace the standard Swagelock ferrules. The interior ends of the 10 sample tubes are attached to separate 1/4-inch o.d. copper vacuum lines which pass through the bottom of the box, through the aluminum skin of the fuselage to the solenoid valve assembly (figure 3). The interior ends of the 2 control tubes are capped. One half-inch i.d. braided fiberglass tubing protects the exposed section of the collection tube, external to the box. This prevents the external section of each tube from softening and sagging at the higher temperatures (i.e., temperatures greater than 350 °F). The internal filter in each tube is positioned within the tube far enough from the ice bath to prevent condensation of water in the filter.

The box has a drain line for the removal of ice-water after a test. The front of the box is jacked up 1 inch, so that water condensing within each tube does not exit the tube or wet the internal filter.

The solenoid valve assembly is an array of 10 solenoid valves, remotely controlled by the data acquisition/control computer so that a sample is drawn for 30 seconds for each sample tube during the 5-minute test period. Downstream of this assembly, one 1/4 inch vacuum line is followed by a particulate filter, which is followed by a Matheson 603 Flowmeter with a restrictor valve which sets the flow. This is followed by house vacuum. This flowmeter is set to draw at 68 glass for each test. Since this flowmeter is external to the fuselage, 30 feet downstream of the point of exiting the fuselage, the sample stream of dried gas flowing through it during a fire test approaches room temperature. The tubes are sealed with plastic caps and placed in a drierite desiccator prior to weighing. The respective flows are measured posttest upstream of the same sample tubes, after the tube filters are removed and the tubes are weighed, to check the flow uniformity from tube to tube.

Two of these sampling assemblies are used in the TC10 water spray tests. One at station 80 at 5 feet 6 inches and one at station 580 at 3 feet 6 inches.

ANALYSIS.

The 12 collection tubes for each sampling station are weighed before and after the test with the internal filter and first upstream retainer removed. The corresponding filters are also weighed before and after each test. The tube weight gain is assumed to be predominantly due to the collection of water vapor. Carbon monoxide, carbon dioxide, oxygen, and other fixed gases with low boiling points pass through the tube with no retention. Water condenses and/or reacts with the drierite to form waters of hydration ($CaSO_4 \cdot 2H_2O$).

A Mettler P163 pan balance with a tara adjustment was used, with a readability of 1 mg. A hollow conical ($i.d._1$= 1/4 in., $i.d._2$= 3 1/4 in., height = 2 1/2 in.) polypropylene sample tube holder was employed to hold the sample tube upright while weighing. The balance calibration was frequently checked using appropriate class P-metric standard weights.

METHOD VALIDATION.

The Teflon FEP tubing was subject to Thermogravimetric Analysis (TGA) heated in zero grade air from 40 °C to 800 °C to determine if the high temperatures generated in the fire tests would cause weight loss of the sample tubes (figure 4). TGA measures weight loss as a function of temperature. It can be seen that the teflon starts to decompose at 350 °C (662 °F). At 500 °C the sample loses 1 percent of its weight. At 720 °C, it loses 100 percent of its weight.

The temperature did not approach 350 °C in the sampling locations in the wide-body fire tests discussed in this report. Temperatures remained below 218 °C (424 °F). Likewise, no significant weight loss was observed for any of the control water vapor collection tubes, indicating that weight loss of the absorption tube itself is not an error in these tests.

The potential error of soot, oil, and acid gases collected in the water vapor collection tubes was minimized by placing a light glass wool filter in the intake end of each tube. This filter was removed before weighing each tube. The weight gain of these filters was low relative to the weight gain of the collection tubes. The greatest filter weight gain was 4 mg. The filters visually appeared to be very effective in trapping the dry black powdery soot, leaving very little discoloration of the downstream parts of the tube.

The weight change of the filters in the control tubes never exceeded 1 mg, indicating that the deposition of soot in the tubes exposed to a 5-minute fire test is not a significant error.

The eighth sample tube from station 80, 5 feet 6 inches, was subjected to Thermogravimetric Analysis from 40 °C to 900 °C at a heating rate of 20 °C per minute, for the baseline TC10 test with no water spray, to determine collection efficiency and any weight loss of compounds other than water. The maximum temperature reached during this 30-second sampling period for this tube was 184 °C (364 °F). The following samples were analyzed:

(1) An intact drierite pellet (pink) on the upstream end of the tube

(2) An intact drierite pellet (blue) on the downstream end of the tube

(3) An intact drierite pellet (blue) from the reagent bottle

(4) An intact drierite pellet (pink) in ambient room air at 75 °F for 3 hours

(5) The intact glass wool plug upstream of the drierite

(6) The intact glass wool plug downstream of the drierite

Figure 5 presents TGA plots of weight loss as a function of temperature for the drierite pellets 1, 2, and 3 heated in dry zero air. The pellets were exposed to room air briefly, while transfering them to the balance pan of the TGA, which most likely resulted in some absorption of moisture. The weight increase for these pellets during the early part of the analysis is due to absorption of moisture from the ambient air which enters the furnace chamber as the sample is loaded. It can be seen from figure 5 that the collection efficiency of this collection tube is excellent, as the downstream pellet has a low and similar water content to the the pellet taken directly from the reagent bottle. The upstream drierite pellet 1, has a considerably greater water content than the downstream pellet.

Figure 6 presents TGA plots of drierite pellets 3 and 4 heated in dry zero air. Drierite becomes anhydrous by 180 °C (356 °F). The curves match fairly closely up to this temperature, indicating that the TGA weight loss up to 180 °C appears to be due primarily to water.

TGA analysis of the glass wool plugs 5 and 6 indicates that the upstream plug had a weight gain of 0.02 mg. However 55 mg of water was collected in this tube. Thus the weight gain of the tube due to higher boiling point molecules seems to be an insignificant error.

Six sample collection tubes from the same baseline test were heated in a drying oven at 180 °C (356 °F). They were placed in a desiccator lined with indicating drierite to cool prior to weighing. This procedure was repeated until a constant weight was measured. A tube weight loss exceeding its weight gain for the tubes with negligible weight gain, indicates that the tube was not 100 percent anhydrous prior to the test. It appears that the pre-test water content of the tubes ranged from 0 to 6 mg.

Tube No.	Station	Tube Weight before Test (g)	Tube Weight after Test (g)	Tube Weight after Drying (g)	Tube Weight Gain (g)	Tube Weight Loss (g)	Gain minus Loss (g)
9	80, 5'6"	10.804	10.881	10.806	.077	.075	+.002
9	580,3'6"	10.963	11.022	10.963	.059	.059	.000
7	80, 5'6"	10.987	11.022	10.982	.035	.040	-.005
7	580,3'6"	10.576	10.622	10.577	.046	.045	+.001
2	580,3'6"	10.716	10.718	10.710	.002	.008	-.006
B2	580,3'6"	10.639	10.641	10.639	.002	.002	.000

Since the tubes return to their original weight or less after heating at 356 °F, little to none of the material collected in the tube had a boiling point exceeding this temperature or was irreversibly bound to the tube packing material at this temperature.

CALCULATIONS.

The flow upstream of the tubes was measured with a Matheson 603 flowmeter. The flow measured was 1.01 liters/minute at 760 mm Hg and 70 °F (21.1 °C). Assuming this room temperature air was dry, 1.01 liters per minute of dry air was drawn through the restricting needle valve of the downstream flowmeter.

During a test, the mass flow into the tube exceeds the mass flow downstream of the tube by the mass of water collected. Since the flow is metered downstream, a flow correction is needed to account for the additional volume of water sampled.

KNOWNS:

Volume of 1 mole of ideal gas at 70 °F, 1 atm. = 24.2 liters

ie) $70\ ^{\circ}F = 21.1\ ^{\circ}C + 273.2\ K = 294.3\ K$ (1)

and $V = \frac{nRT}{P}$ where $R = 8.2057 \times 10^{-2}$ l atm $mol^{-1}deg^{-1}$

$V = 1(8.2057 \times 10^{-2})(294.3)$

$V = 24.2$ liters

The Molecular weight of water = 18.01g mol^{-1}

$MW_{H2O} = 2(1.008) + 15.994$ (2)

$MW_{H2O} = 18.01\ g\ mol^{-1}$

IF:

100% pure water vapor at 1 atm., 70 °F is drawn INTO the tube at an actual flow rate of 1.01 l min^{-1} with no other gas present (note: this is nonsense but assume the water is entirely in the vapor phase), and water vapor behaves as an ideal gas,

THEN:

0.505 liters is drawn INTO the tube in 30 seconds

AND:

$$\text{Mass water collected} = \frac{1\ \text{mole}}{24.2\ \text{l}} \left(\frac{18.01\ g\ H_2O}{\text{mole}}\right)\left(\frac{.505\ \text{l}}{\text{tube}}\right) \quad (3)$$

$= 0.376$ g

Therefore 0.376g = mass of water vapor sampled at 70 °F, 1 atm per tube if $P_{ATM} = P_{H2O}$, and actual flow into tube = 1.01 l min^{-1}

For a TC10 test, the volume percent water vapor in air can be calculated based on the weight of water collected in the water vapor collection tube, and the flow rate of dry air through the downstream needle valve. Equation 4 gives the volume percent water vapor for the TC10 fire tests when the downstream flow of dry air is 1.01 l/min at 70 °F.

$$\text{The corrected \% water in aircraft cabin} = \frac{\text{\_\_\_\_g water}}{0.376 + \text{\_\_\_\_g water}} \times 100 \qquad (4)$$

EVALUATION OF TEST RESULTS.

A full description of this widebody water spray optimization study can be found in reference 2. Five rows of seats were placed in the cabin by an open door adjacent to an external fuel fire water vapor was measured at two locations in the fuselage for this test series: station 80 at 5 feet 6 inches and station 580 at 3 feet 6 inches. These measurement locations were not in the water spray zones. Test 2 was the baseline test with no water spray and water spray was utilized in tests 3 through 8 at various nozzle flow rates, and various water volumes, for zoned spray and split zoned spray configurations.

Figures 7 and 8 present the water vapor concentration, as calculated in equation 4, as a function-of-time for these sampling locations. Test results show that concentrations of water vapor reached as high as 17 percent for the baseline test at station 80 at 5 feet 6 inches. The baseline water vapor concentrations were lower at station 580 at 3 feet 6 inches and reached a maximum of 14 percent. The water vapor generated in the baseline test is a thermal decomposition product of the interior materials and of the JP4 fuel.

It can be seen from these figures, that the concentration of water vapor as a function-of-time for the water spray tests is similar to the baseline tests. The water vapor generated in the water spray tests is both a thermal decomposition product and a product of the vaporization of the fine water mist. Since the water spray delays the temperature rise in these locations, and the concentration time curves are similar for baseline and water spray tests, the total thermal survival hazard is reduced for these water spray tests at these locations.

Figures 9 and 10 present the water vapor concentration as a function of cabin temperature at these sampling locations. The concentration of water vapor at it's dew point is indicated by a dashed line, and the baseline test water concentrations are indicated by a heavy black line. These figures indicate that for temperatures greater than 150 °F, the contribution of the vaporization of water to the total water vapor content of the air is about the same as the contribution of the thermal decomposition products, at the same air temperature. It can also be seen from these figures that the water vapor concentrations for all tests are significantly lower than the dew point concentrations.

SUMMARY

The method of collection and analysis of water vapor described here is appropriate for combustion gas analysis. It has been shown to be free of organic and particulate interferences. The quantities of water measured in full-scale fire tests are so high that acid gas interferences are not a significant error.

Advantages of this method are it's simplicity, low cost, self calibration, and the elimination of heated sample lines and filters.

REFERENCES

1. Speitel, L., Filipczak, R., Guastavino, T., "Methods of Collection and Analysis of Toxic Gases from Large Scale Fire Testing of Aircraft Interior Materials: Equipment/Systems Description," Federal Aviation Administration, Report No. DOT/FAA/CT-TN83/18, August 1983.

2. Marker, Timothy, R., "Widebody Cabin Water Spray Optimization Tests," Federal Aviation Administration, Report No. DOT/FAA/CT-TN93/29, August 1993.

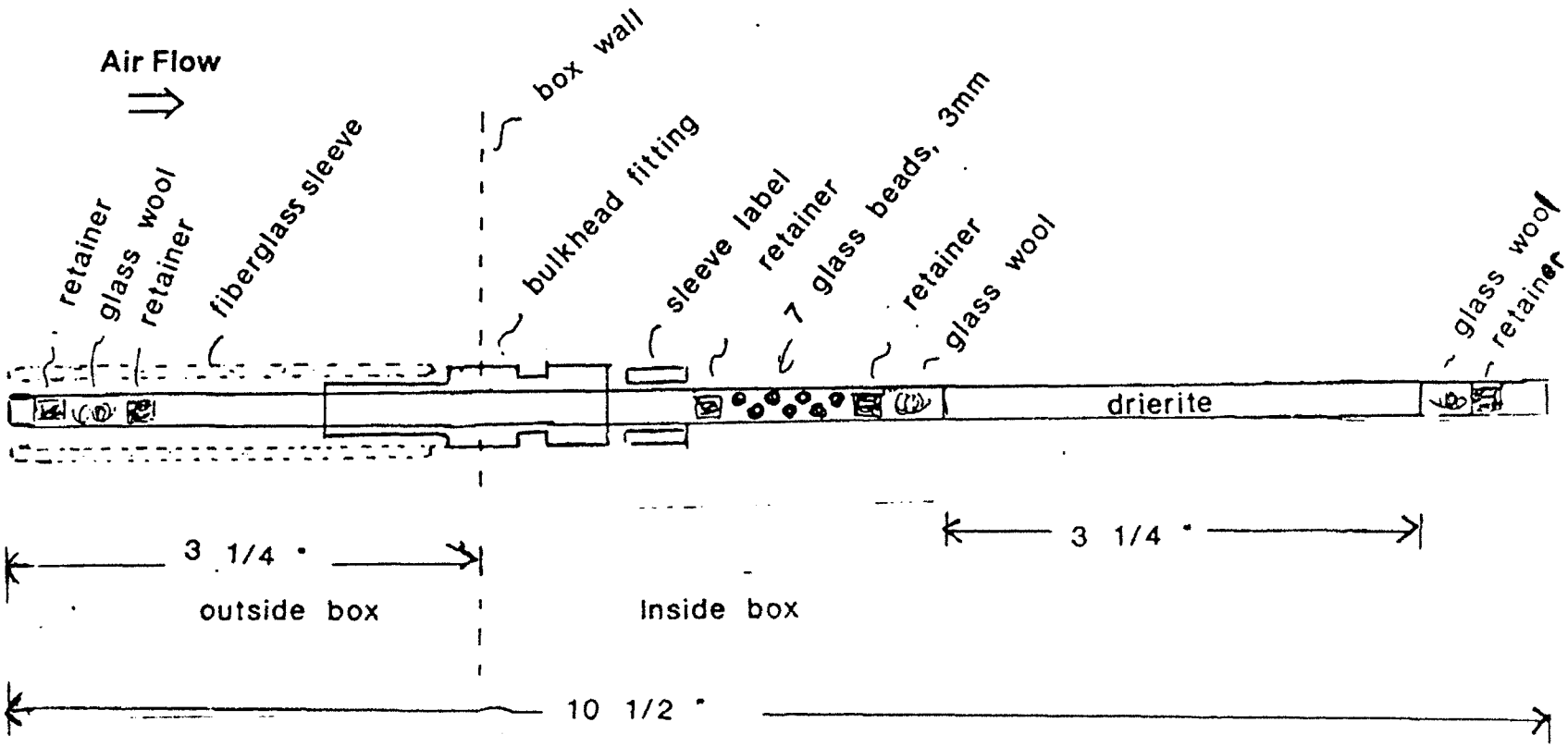

FIGURE 1. WATER VAPOR COLLECTION TUBE MOUNTED THROUGH ICE-WATER BATH

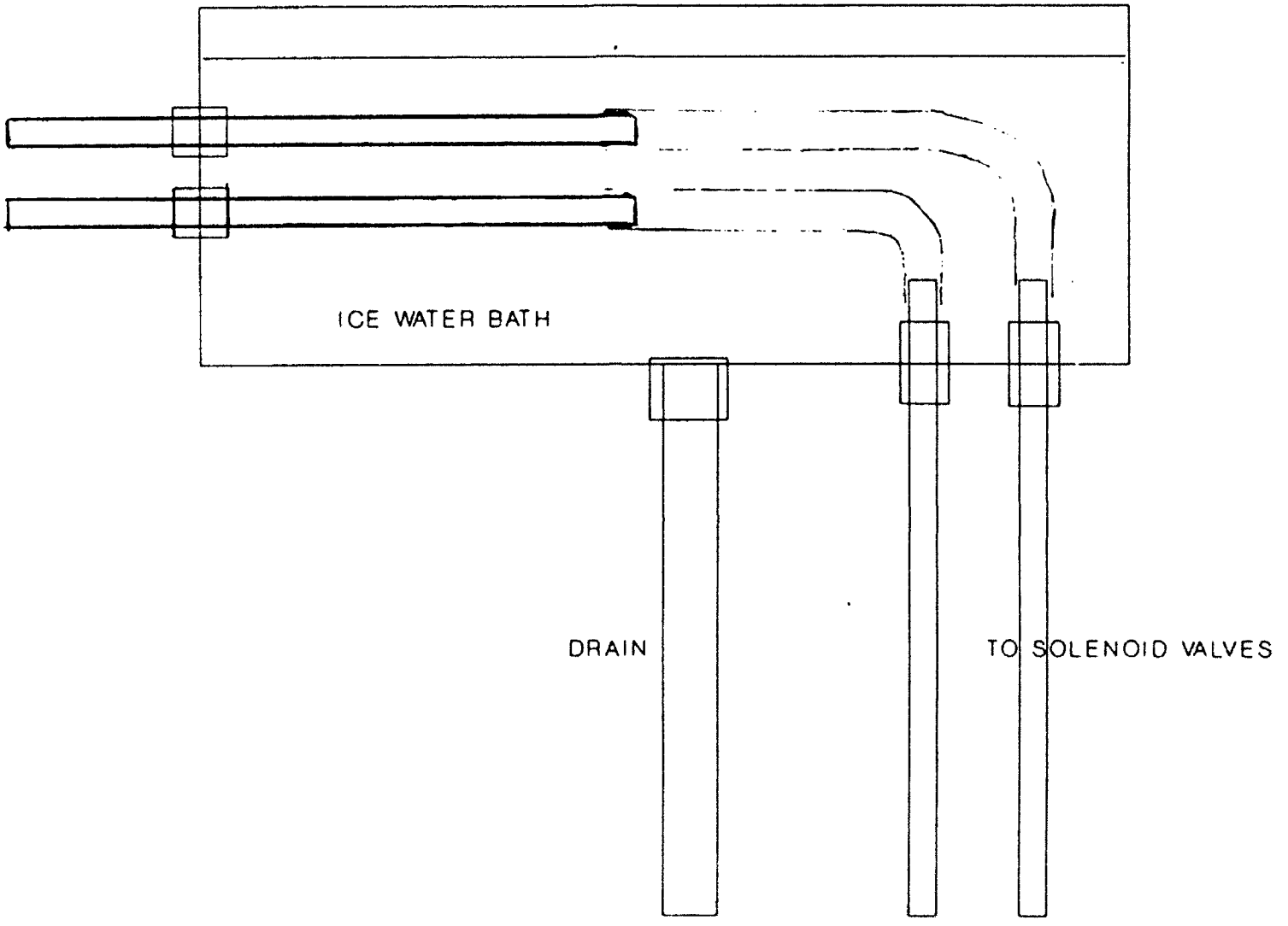

FIGURE 2. HOUSING FOR WATER VAPOR COLLECTION TUBES

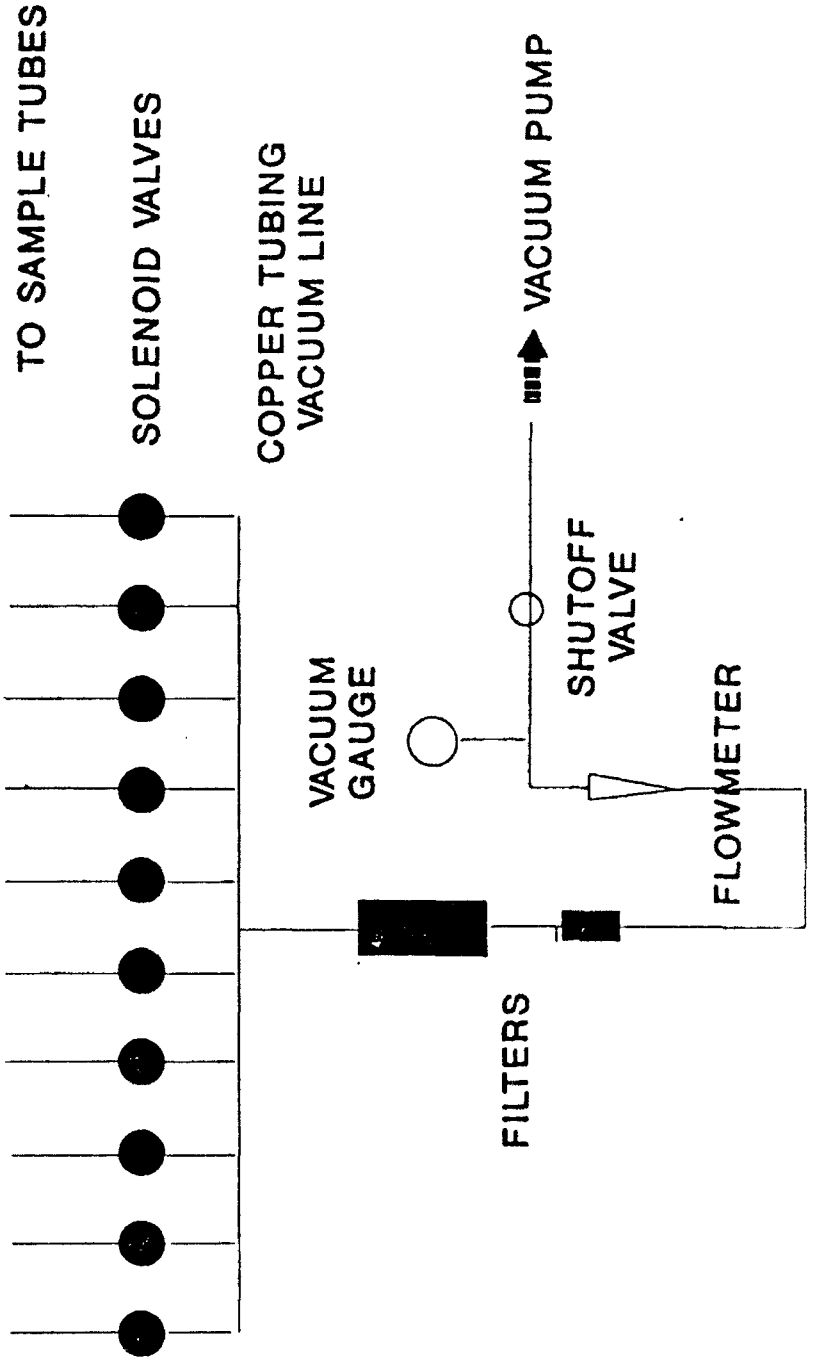

FIGURE 3. SAMPLING SYSTEM DIAGRAM

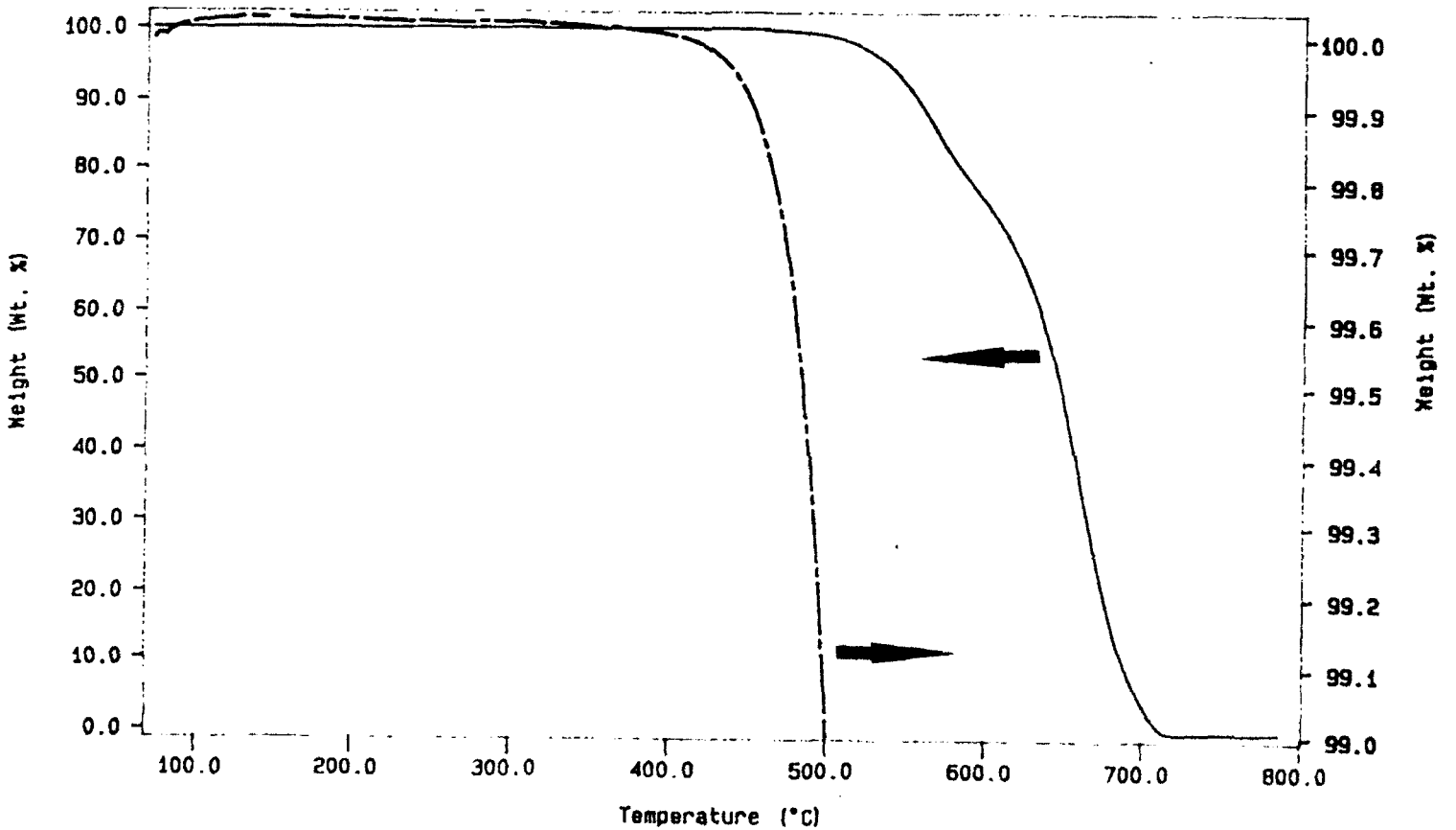

FIGURE 4. THERMOGRAVIMETRIC ANALYSIS OF TEFLON FEP

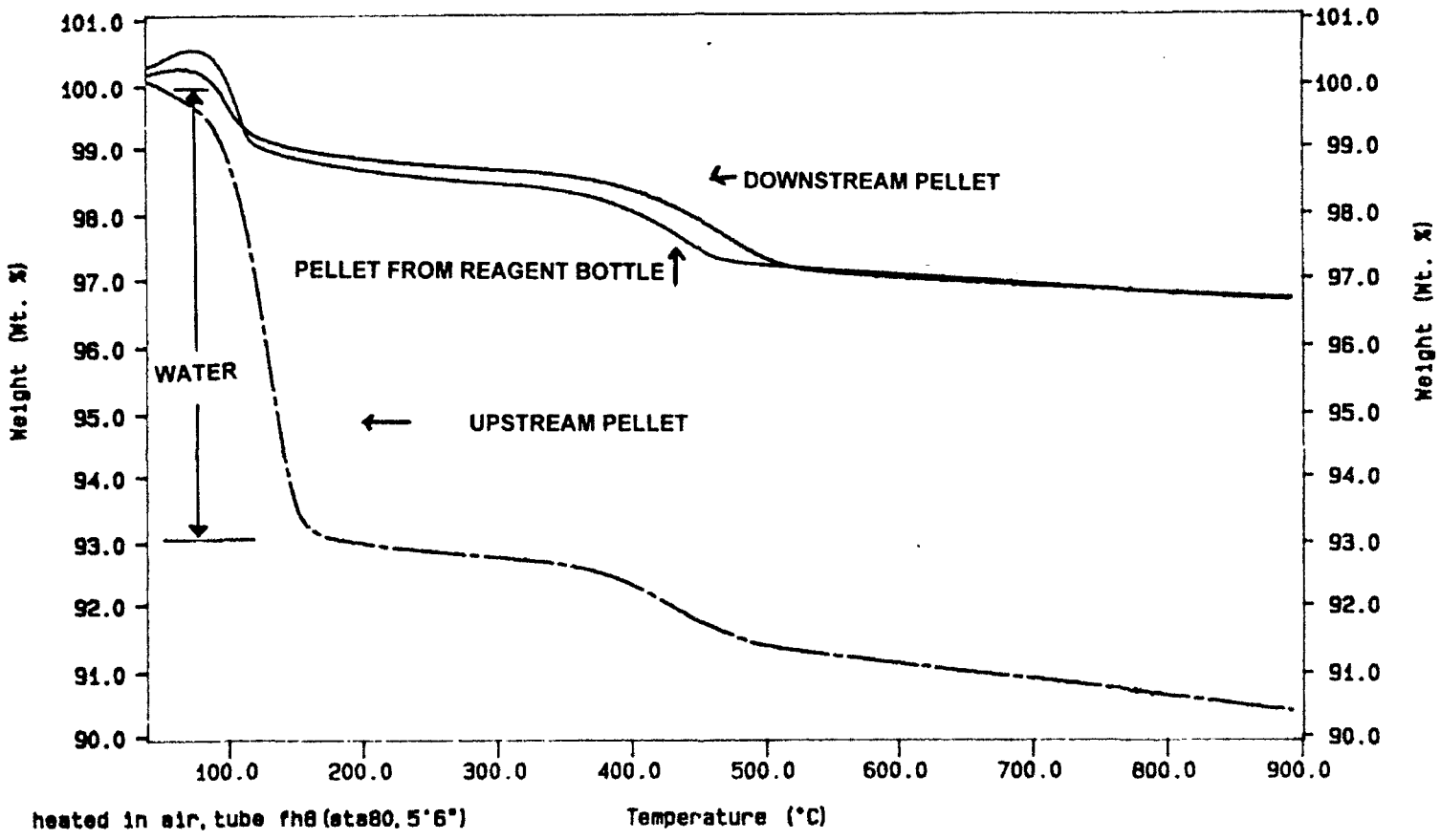

FIGURE 5. THERMOGRAVIMETRIC ANALYSIS OF DRIERITE PELLETS

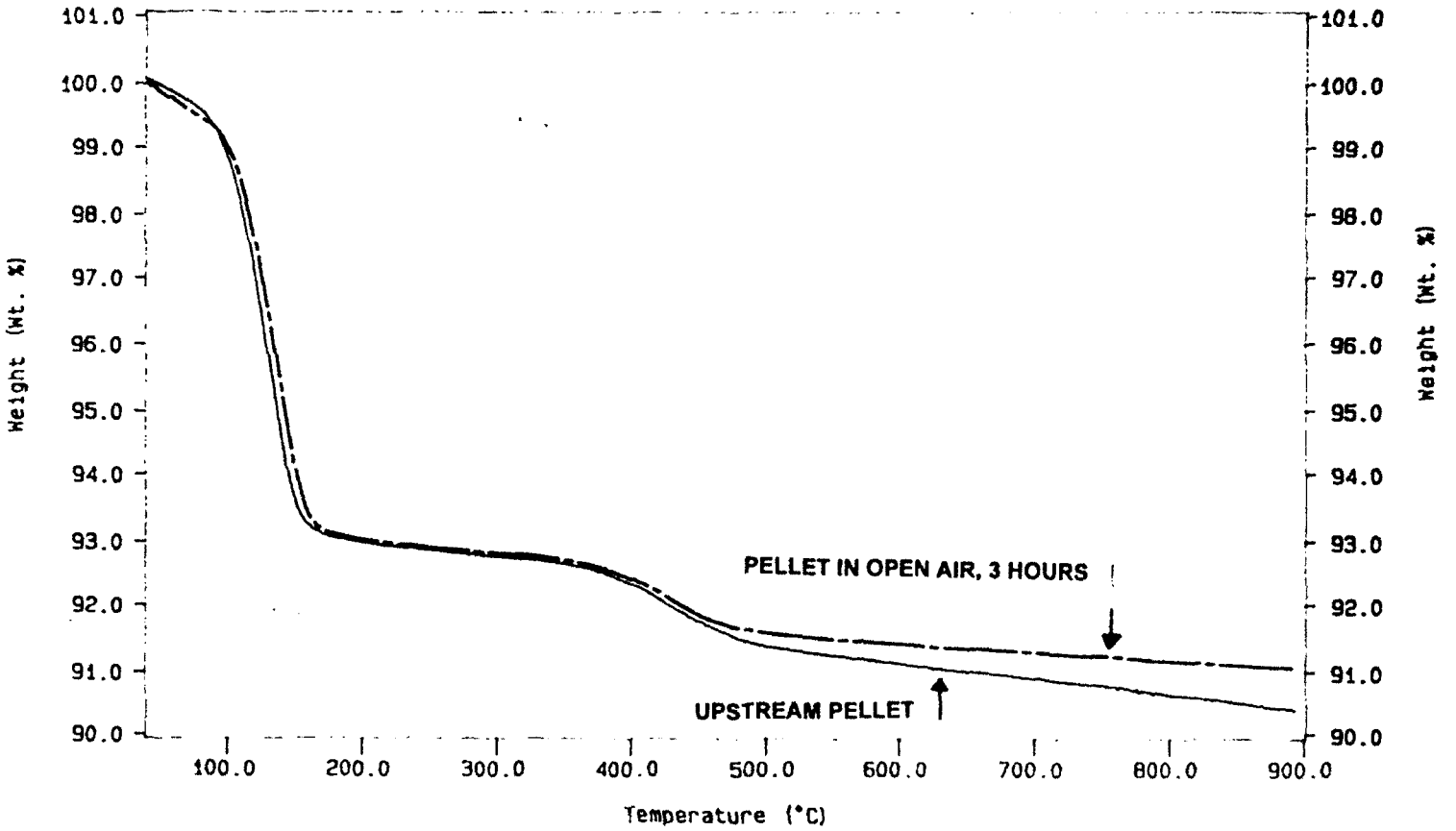

FIGURE 6. THERMOGRAVIMETRIC ANALYSIS OF DRIERITE PELLETS

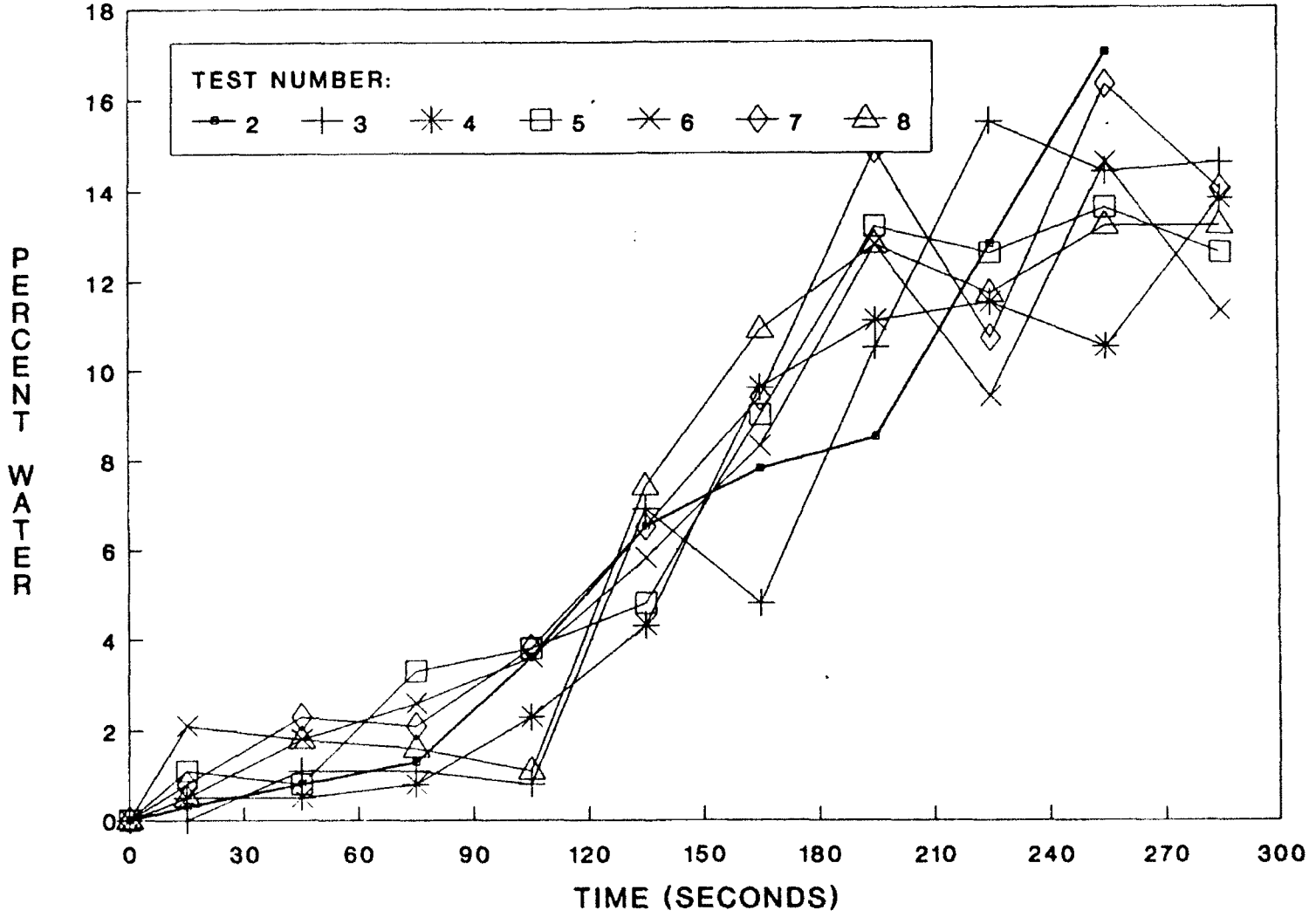

FIGURE 7. COMPARATIVE WATER VAPOR CONCENTRATIONS FOR WIDE-BODY AIRCRAFT CABIN WATER SPRAY TEST AT STATION 80, 5 FEET 6 INCHES

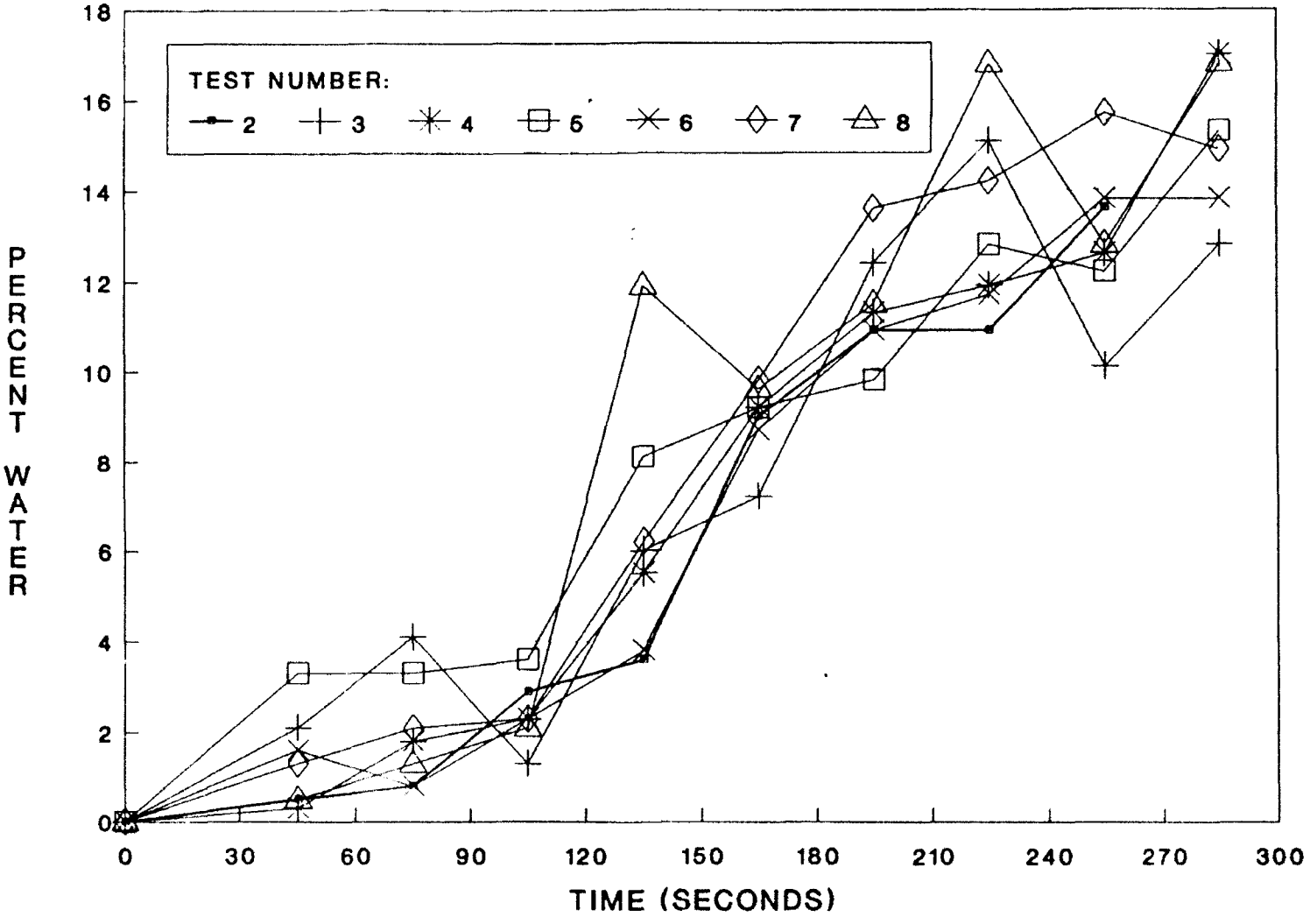

FIGURE 8. COMPARATIVE WATER VAPOR CONCENTRATIONS FOR WIDE-BODY AIRCRAFT CABIN WATER SPRAY TEST AT STATION 580, 3 FEET 6 INCHES

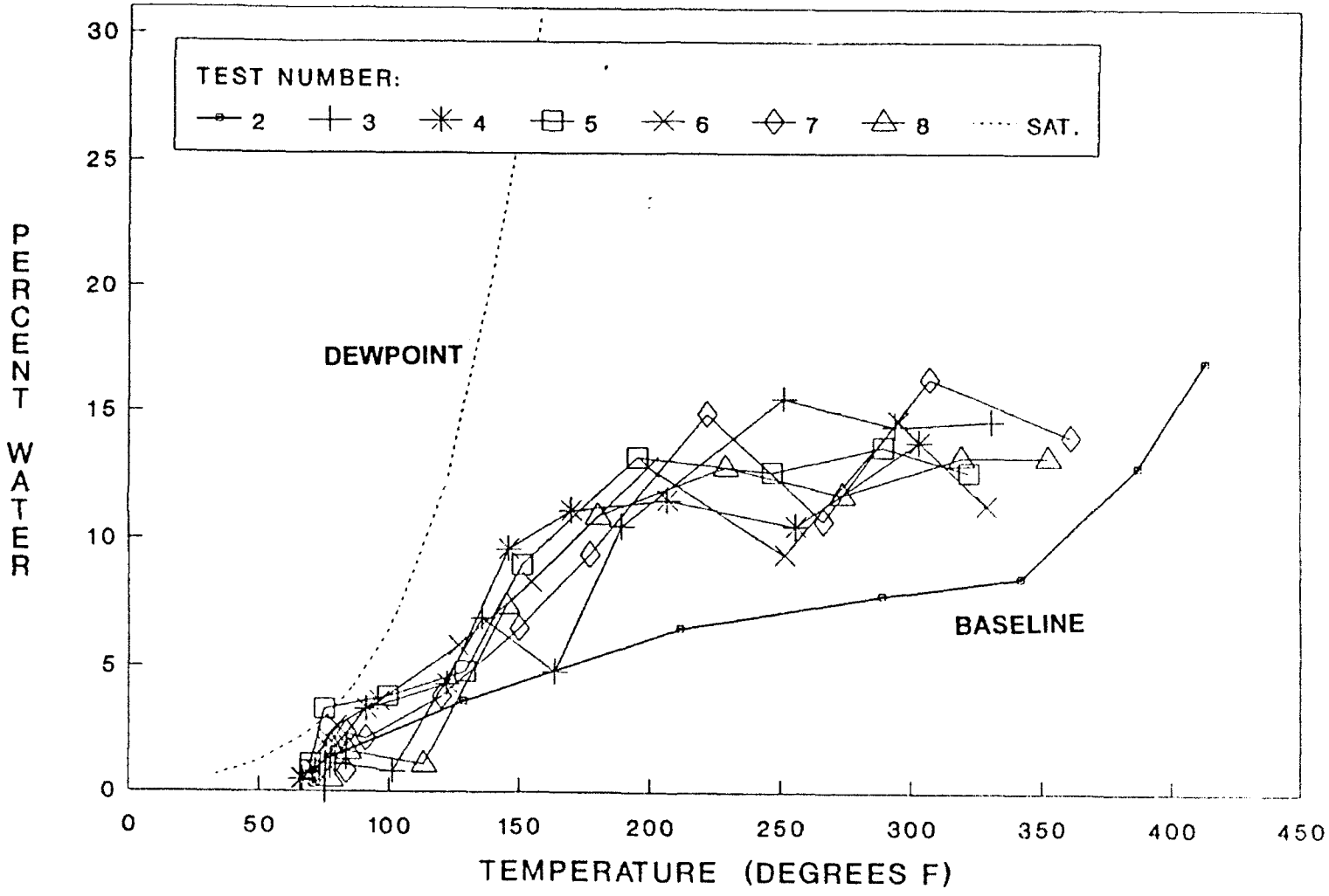

FIGURE 9. COMPARATIVE WATER VAPOR CONCENTRATIONS AS A FUNCTION OF TEMPERATURE FOR WIDE-BODY AIRCRAFT CABIN WATER SPRAY TESTS AT STATION 80, 5 FEET 6 INCHES

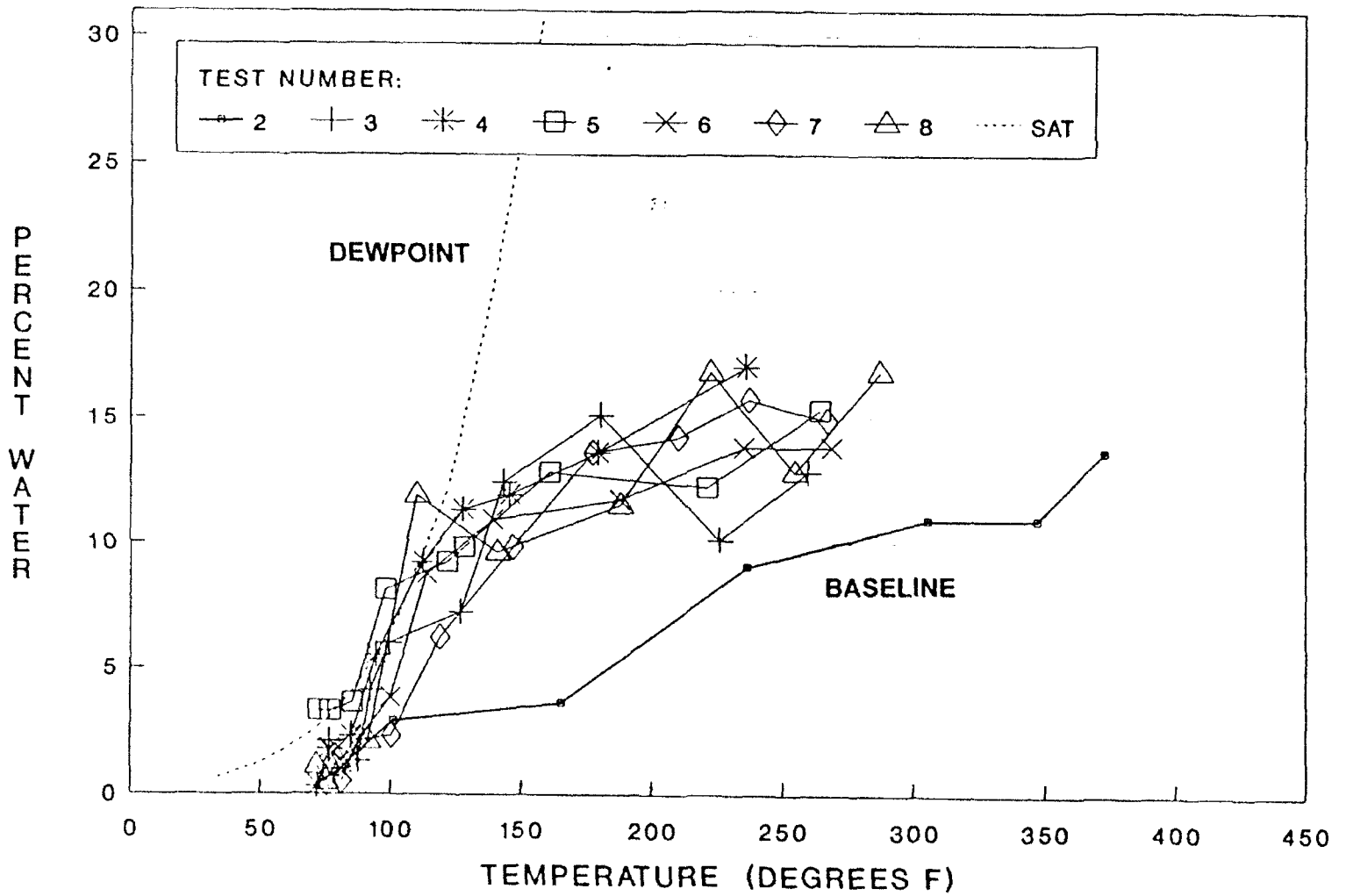

FIGURE 10. COMPARATIVE WATER VAPOR CONCENTRATIONS AS A FUNCTION OF TEMPERATURE FOR WIDE-BODY AIRCRAFT CABIN WATER SPRAY TESTS AT STATION 580, 3 FEET 6 INCHES